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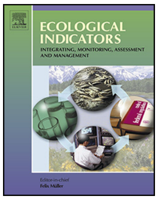

Emergy and exergy evaluation of a dike-pond project in the drawdown zone (DDZ) of the Three Gorges Reservoir (TGR)

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ABSTRACT

The dike-pond system was a form of ecological engineering that was a component of successional dikes and ponds along the banks of the Pengxi River in the drawdown zone (DDZ) of the Three Gorges Reservoir (TGR). The application of science-based evaluation system was appropriate for the flows of emergy in this agricultural ecosystem. The Emergy Analysis (EmA) has the ability to transform different types of inputs to a common form to allow meaningful comparisons across different systems. This study made use of the emergy analysis that assessed two different types of farming methods in the DDZ of the TGR. One method was planning crops in a dike-pond system (model I), and the other method was conventional agriculture (model II). In addition, the Exergies of both yields of agriculture methods were calculated, and the Exergy and Emergy Density (ED) were combined to explore the quality of these methods. The results showed that the two models relied on different resources. The ED yield of both models were similar, but the emergy investment of model II was greater than that of model I. Model II also used less renewable energy input to the agricultural systems than model I. The agricultural emergy sustainability index (AESI) of model I system ($AESI = 2.4 > 1$) was greater than that of model II system ($AESI = 0.5 < 1$), which indicated that the sustainable development of model I was stronger than that of model II in the DDZ of the TGR. The ratio Exergy/Emergy density ($R_{ex/em}$) in the two models of different agricultural system were 121.52×10^{-3} J/sej (Model I) and 24.19×10^{-3} J/sej (model II). Model I was greater than model II, and the result intimated that the model I agricultural system was a new method in the DDZ, but it was older and closer to the steady state than model II. The Emergy and Exergy analysis certifies that model I has a more acceptable and more sustainable development potential and is more stabilized in the DDZ of the TGR.

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1. Introduction

Water levels in the Three Gorges Reservoir (TGR) are operated between 145 m during the summer and 175 m above sea level during the winter, which is opposite to natural river flooding rthythms and causes the abnormal undulation of water from 2007 to 2014 (see Fig. 1). This alternation creates a large littoral zone, estimated to be 34,893 ha (Zhang, 2008), when the TGR stored water to obtain important services such as power generation and flood control as is done in other reservoirs around the world. For the years of operation, the environment in the TGR combined with the elevation creates contentious issues, involving society, economics, environment and ecology in the DDZ, such as immigration and the carrying capacity of the environment in the reservoir area (Tan et al., 2008; Xu et al., 2011), the ownership of land adscription (Li et al., 2011, 2013), agricultural nonpoint source pollution (Pan et al., 2008; Zhang et al., 2010), over grazing and irrational cultivation (Li et al., 2011; Shi, 2011; Shen et al., 2010), water quality deterioration (Guo and Li, 2012; Ma et al., 2011), reservoir-induced seismicity and geological instability (Wang et al., 2014), loss of biodiversity and changes in species communities (Duan et al., 2009; Sun et al., 2010; Gao et al., 2010). These issues had a significant impact on people living in the reservoir area and conflicts during human-land-economic interactions are particularly evident.

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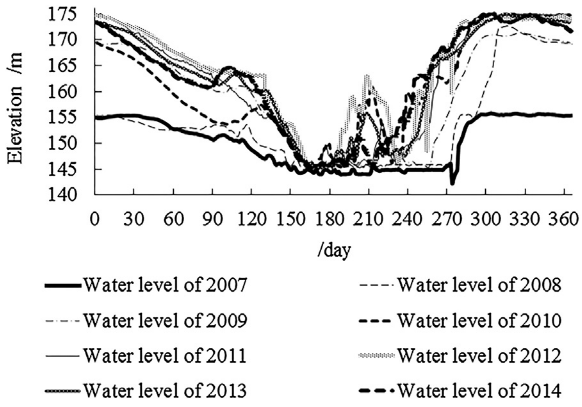

Fig. 1. Submerged time among different altitudes in drawdown zone, 2007–2014.

Unreasonable farming methods directly resulted in serious soil erosion and extensive use of pesticides and fertilizers were harmful to the TRG ecological environment. Therefore, a quantitative evaluation and comparison of the particular environmental condition of the DDZ that simultaneously considers a lower investment of resources, stronger sustainable agricultural and more ecological factors, is an essential first step to documenting their relative sustainability.

Dike-pond engineering is an important form of ecological engineering and an eco-friendly (Willison et al., 2013; Yuan et al., 2013) approach near the banks of the river in the DDZ, which is a series of terrace complexes consisting of dikes and ponds flooded seasonally. China has an agricultural heritage of dike-pond engineering in a river basin's alluvial-proluvial zone in the Pearl River Delta, which we borrowed. The theory of dike-pond engineering was that plant and animal wastes feed the fish and fertilize the pond, organically rich mud is dug from the pond bottom and spread three times a year as a fertilizer over the dikes, and throughout the year, runoff from the dikes gradually returns the mud to the pond bottom, where its nutrients are restored (Guo and Li, 2012; Lo, 1996). Li et al. (2011, 2013) designed dike-pond engineering based on the traditional mulberry dike-fish pond, and evaluated the method for the economic production of crops, but the results was not summarily analysed with consideration of economic, ecological, environmental and societal factors. Because the economy, ecology, environment and society have different units, they could not be directly calculated and compared because of the battier of energy (Odum and Odum, 1983; Lan and Qin, 2001). However, the Emergy Analysis (EmA) has the ability to transform different types of inputs to a common form (solar energy equivalents) to allow meaningful comparisons across different systems (Odum, 1996).

EmA was defined as a form of energy assessment that quantifies values of natural and economic resources to quantify the value of large-scale environmental support to the human economy, which has been performed on the regional scale (Chen and Chen, 2013; Jiang et al., 2009), the national scale (Chen and Chen, 2006, 2010, 2011a) and the global scale (Chen et al., 2011; Chen and Chen, 2012). In addition, some renewable energy technologies have also been evaluated with emergy, such as hydropower plants (Zhang et al., 2014; Cheng et al., 2015), wind power plants (Yang et al., 2013), biogas engineering (Wu et al., 2014, 2015), and this analysis has also been applied to assess nonrenewable energy cost and greenhouse gas (GHG) emissions of ecological engineering works (Chen and Chen, 2011b; Shao and Chen, 2013), and building construction engineering (Han et al., 2014), and constructed wetlands (Chen et al., 2009). A few studies have been conducted to assess typical agricultural systems via the emergy approach (Lu et al., 2003, 2005, 2010; Zhang et al., 2007; Jiang et al., 2007). Lu et al. (2014) used emergy to evaluate dike-pond engineering in river basin management in the Pearl River Delta. Edward and Torbjörn (2003), Martin et al. (2006), Vassallo et al. (2007) used emergy to discuss agricultural systems and fisheries in Australia, America and Italy, respectively.

Exergy, as previously defined, can measure how much entropy is pumped out from the system and how far from the thermodynamic equilibrium the system is maintained (Bendoricchio and Jorgensen, 1997). It reflects how self-organized ecological systems develop by keeping their state as far as possible from thermodynamic equilibrium. The modified exergy function proposed by Jørgensen, later defined as eco-exergy, is defined as the free energy of all of the biotic compositions in an ecosystem compared with their environment, which can be used to measure the organization level of ecosystems (Jørgensen and Mejer, 1977; Mejer and Jørgensen, 1979). The advantages of application of exergy or eco-exergy may be described as follows: (1) it is a measure of survival as it accounts for the distance from thermodynamic equilibrium due to the content of biomass and information; (2) due to its property of referring to an energetic approach, and to its strong correlation to ascendency that accounts for network complexity and articulation, it seems to be a good candidate to describe the ecosystem evolution; and (3) it can account for changes in the properties of the system (Jørgensen, 2002). Exergy or eco-exergy has been applied successfully in many studies where it has proved to be successful in evaluating the organizational state of wetlands and aquatic ecosystems (Libralato et al., 2006; Jørgensen, 2007a; Austoni et al., 2007; Pranovi et al., 2007), but no application to dike-pond systems has been published yet.

The application and integration of emergy and exergy in the evaluation of the efficiency of systems in self-organization is currently one of the frontiers of emergy study (Bastianoni and Marchettini, 1997; Bastianoni, 1998; Jørgensen et al., 2004, 2005; Bastianoni et al., 2006, 2007; Lu et al., 2011, 2012). In this paper, both emergy and exergy theories and analysis methods were applied to evaluate and compare a dike-pond system method with a traditional framing system method in southwest China. The case study was performed by means of the emergy accounting method coupled with a decomposition evaluation technique, which classified the energy systems into four categories as follows: natural resources, social resources, capital and dissipated heat. The paper was applied to a calculated series of Emergy Indices (EI), ratios and $R_{ex/em}$ (the ratio Exergy/Emergy density). The purpose of evaluating two models was to illustrate the different energy structures to improve the quality of decision-making processes in planning in the DDZ. Our results can be applied to improve to the management in the DDZ.

2. Location and methods

2.1. Location

The present study was carried out in Laotudi Bay, located at 108°34′5.046″–108°34′21.440″ E, 31°9′0.798″–31°9′9.9674″ N, which was near the Baijia Creek, a tributary of the Pengxi River (shown in Fig. 2), in the northeast of Chongqing municipality in China. The region was characterized by north subtropical humid monsoonal climatic conditions with average annual precipitation of 1053.15 mm, average annual temperature of 18.2 °C, effective solar radiation average annual between 3600 and 3700 MJ/m^2, sunshine duration average annual about 1400 h (Zhao et al., 2009). The dike-pond engineering ecosystem consisted of 25 cascading terraced ponds distributed from 159.49 m to 172.39 m above sea level. Slope was gentle, with the average slope less than 10°. The dike-pond was completely emersed in mid-April, and submerged in September. When it had heavy rain in July, parts of dike-pond with low elevation could be flushed temporality, as in July 2012. Con-

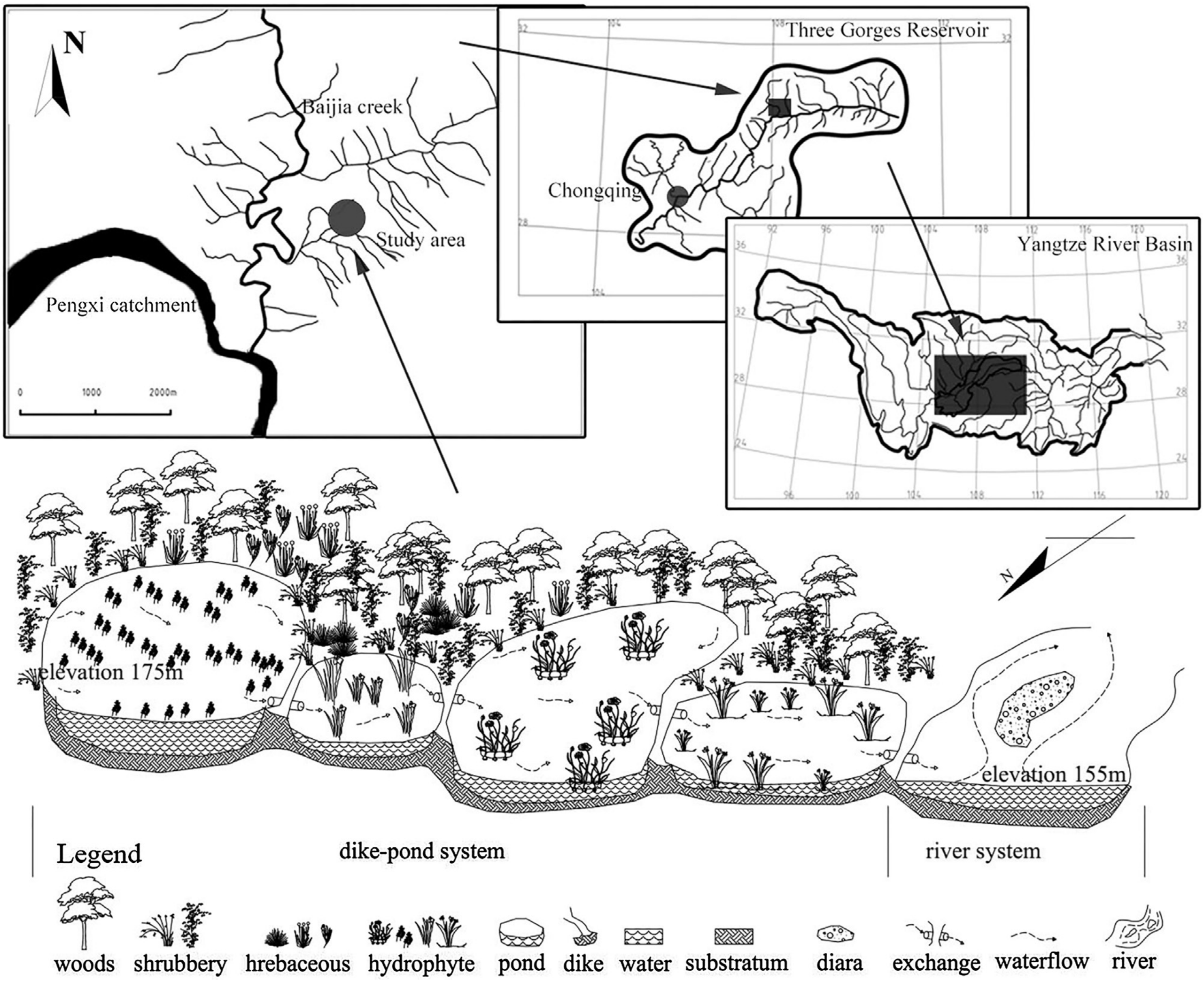

Fig. 2. The dike-pond model of the Baijia Creek, a tributary of the Pengxi catchment, Kaixian.

trast area was conventional agriculture, elevation from 171.15 m to 177.11 m, higher than the dike-pond area, but had steep slope, with an average slope of 20°. The dike-pond system in the DDZ was about 19829.35 m^2 and the traditional farming systems of crop cultivation covered 38188.33 m^2.

2.2. Methods

2.2.1. Emergy analysis theory

Emergy analysis was the available energy used in transformations directly and indirectly to make a product or service. Emergy was measured in emjoules. Sunlight, fuel, electricity, and human service and all other resource flows could be put on a common basis by expressing them in the emjoules of solar energy required to produce them, which was expressed as solar emjoules (sej). Emergy analysis took into account the quality of each form of energy multiplying each quantity of energy by its solar transformity. Solar transformity was defined as solar emergy per unit energy (sej/J) (Odum, 1988). For example, the solar transformity of wood was 4000 solar emjoules per joule (sej/J) because 4000 solar emjoules of environmental inputs were required to generate a joule of wood. The solar transformity of sunlight absorbed by the earth is defined as 1 sej/J. Transformities had been calculated for a wide variety of resources, commodities, and renewable energies, and could be found in past publications (Odum, 1996), and a series of emergy folios (Brandt-Williams, 2002; Kangas, 2002; Brown and Bardi, 2001; Odum, 2000; Odum et al., 2000).

2.2.2. Exergy calculation

The following formulas were employed for the calculation of exergy of the two agricultural system (Jørgensen, 2007b).

$$E_x = 18.7\,\text{kJ/g} \times \sum_{i=0}^{n} C_i \beta_i \qquad (1)$$

where β_i is a weighting factor accounting for how much information is contained in the ith organism, C_i is the concentration in, for example, grams per liter of the ith organism. The unit applied is g detritus equivalents/m^2. By multiplication by 18.7 the results are obtained in kJ/m^2, as the average exergy of detritus is 18.7 kJ/g.

$$\beta = 1 + \frac{\ln\left(20^{C^{***}}\right)}{7.43 \times 10^5} \qquad (2)$$

where 7.43×10^5 is the contribution of detritus to the exergy in g/l; the c-values, or the amount of DNA in picograms that is contained in a haploid nucleus of the plant cells in bp, were obtained from the plant DNA c-values Database of Royal Botanic Gardens, Kew, UK. and the Animal Genome Size Database of University of Guelph, Canada. For those species not in that database, the mean c-values for the genus or families that they belong to were used. The c^{***} is

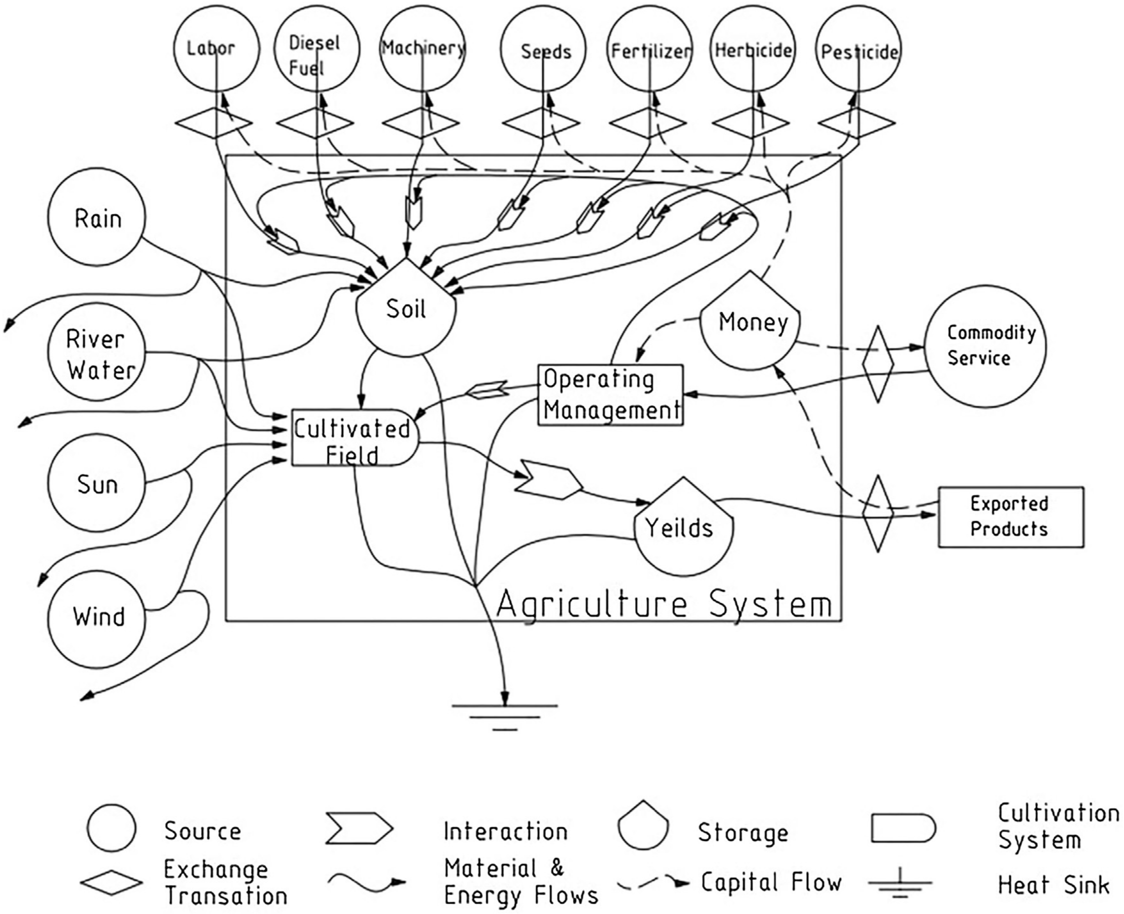

Fig. 3. Conceptual framework for evaluating the agriculture land system based on the emergy system.

the number of nucleotide triplets, or the maximum coding capacity because each adjacent triplet of nucleotides non-repetitive DNA corresponds a transcribed RNA-signal and it is equal to 1.63×10^8 times the c-value.

2.2.3. Emergy system arrangement

The sequence of emergy analysis were three parts. First, we needed search the datas on surrounding, topography, economic, ecology and society of location. Then we used the emergy system symbols of Odum H. T. to draw the agriculture land system diagrams to design an energy flow of the system and identify all areas of energy use, their relationships, and categories (Fig. 3). We organized the different inputs into emergy evaluation tables and converted all components of the system into emergy by multiplying by relevant transformities, which refers to the emergy required to obtain one joule or gram of a product or service. Transformity is not only the 'transformation factor' used to calculate emergy from other initial units of measure, but also reflects the varied hierarchy and quality of different types of energy in the system. We aggregated emergy flows of the agriculture production system and analyzed the structure of the energy inputs of the system. Finally, we calculated Emergy Indices (ELR, AEYR, AESI) to assess the system. Moreover, we used a sensitivity analysis to assess the impact of transformity uncertainty on the evaluation results Based on the results of emergy evaluation, we developed methods to improve the development of this system.

2.2.4. The datas of agriculture system

Meteorology datas were got from weather forecast section. The datas of design dike-pond were got from location. Rain, wind, were considered co-products of sunlight in the emergy analysis; thus, to avoid double counting, only the item with the highest value was considered in the total amount of emergy (Odum, 1996). Because questions about the baseline have not yet been resolved and transformities in this case were relative to the 15.83×10^{24} sej/year standard (Odum, 2000). All calculated transformities, starting from the previously used standard of 9.44×10^{24} sej/year, were multiplied by 1.68 (Odum et al., 2000).

2.2.5. The conceptual framework agriculture system

The conceptual framework of the agriculture system comprised five parts, natural resources, social resources, agriculture system, yield and heat sink. Natural resources included important flows referred to as sunlight, rain, river water, wind and soil erosion in the agriculture system. Social resources included important flows such as labour, seeds, machinery, fertilizer, diesel fuel, pesticides, fertilizers and human management. The dike-pond system (model I) planted Chinese three-leaf arrowhead (*Sagittaria trifolia var. sinensis*), wild rice (*Zizania latifolia*), Chinese water chestnut (*Eleocharis dulcis*), water chestnut (*Trapa bispinosa*), water spinach (*Ipomoea aquatica*), lotus (two varieties: *Nelumbo nucifera*, normal and 'space-travelled'), Chinese celery (*Oenanthe javanica*), rice (*Oryza sativa*) in 25 pieces of dike-ponds. Human management includes reinforcement of the dike-pond, plowing, weeding and harvesting. The purchase of resources consists of the purchase of seeds, machinery, tools, fuel and other materials. The conventional agriculture planting pattern (model II) uses mainly terraced farmland, producing sesame (*Sesamum indicum*), sweet potato (*Ipomoea batatas*), maize (*Zea mays*), rice (*Oryza sativa*). With the exception of reinforced terraced farmland, plowing, weeding and harvesting,

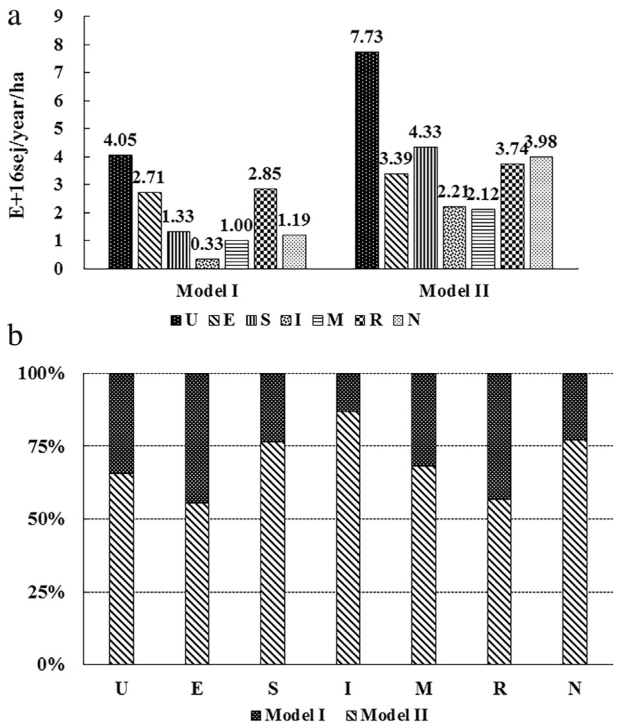

Fig. 4. Structure of emergy inputs for the agriculture land systems ((a) Aggregated structure of emergy inputs, (b) Contrasted of the aggregated structure on ED).

human management includes the application of fertilizers, pesticides, insecticides. The purchase of resources includes pesticides, fertilizers and more.

2.2.6. The indices and ratios

In this paper, the indices and ratios were shown in Table 1.

3. Results

3.1. Emergy input structure

As shown in Fig. 4a, the total emergy density (ED) input to the model I system on the farm was 3.54×10^{16} sej/year/ha, and the input to the model II system on the farm was 2.85×10^{16} sej/year/ha. Based on this result, the total ED input of the model I system was more than the input to the model II system. The natural ED input to the model I system on the farm was 1.37×10^{16} sej/year/ha, and the input to the model II system was 0.95×10^{16} sej/year/ha, which accounted for 38.59% and 33.24% of the total ED input, respectively. The social ED input to the model I system on the farm was 2.17×10^{16} sej/year/ha, and the input to the model II system on the farm was 1.90×10^{16} sej/year/ha, which accounted for 61.33% and 66.66% of the total ED input, respectively. As shown in Fig. 4b, the emergy input to the model I system on the farm (4.05×10^{16} sej/year) was general less than the emergy input to the model II system (7.73×10^{16} sej/year), and the result manifested the model I system was mainly made use of more renewable energy and less social energy, which could save energy and cycle resources in high power consumption period.

Natural emergy flows were directly available to the system, such as solar radiation, wind and rain. Rain and wind were considered co-products of sunlight in the emergy analysis; thus, to avoid double counting, only the item with the highest value was considered in the total amount of emergy. Of the local emergy flows directly available to the system, river water had the highest value and had the most influence on the crops grown. The renewable ED input to the model I system on the farm was 1.66×10^{16} sej/year/ha, and the input to the model II system on the farm was 1.25×10^{16} sej/year/ha (see Fig. 4a), which accounted for 46.97% and 43.77% of the total ED input, respectively. The non-renewable ED input to the model I system on the farm was 1.88×10^{16} sej/year/ha, and the input to the model II system on the farm was 1.60×10^{16} sej/year/ha (see Fig. 4a), which accounted for 53.03% and 56.23% of the total ED input, respectively.

In Table 2, for model I system production, ED from rainwater represented the largest contribution to production (22.70%), which was 8.04×10^{15} sej/year/ha. River water and labour were 5.63×10^{15} sej/year/ha and 5.03×10^{15} sej/year/ha, occupancy were 15.89% and 14.19%, respectively. Occupancy of machine was less than 1%. Occupancy of fuel and seeds were 20.96% and 25.79%. The rain water, river water and labour were chief influence to the model I system because of low altitude and complex change in the water level. For model II system production, ED from rainwater represented the largest contribution to production (30.07%), which was 8.58×10^{15} sej/year/ha. Fuel and labour were 3.86×10^{15} sej/year/ha and 5.55×10^{15} sej/year/ha, occupancy was 13.52% and 19.47%, respectively. The model II system was different from the model I system on making use of the energy, because the model II system adopted conventional agriculture management and used fertilizer, herbicides and chemical pesticides and was high altitude with less affect of change in the water level.

The machine emergy input to the model II system was 7 times than the model I system. Fuel emergy input to the model II system was 10 times than that input to the model I system. The emergy of the purchased seeds input to the model II system was 3 times than that input to the model I system. The reinforcement dike-pond and weeding emergy input to the model I system was 9 times that input to the model II system. Harvesting labour emergy inputted to the model I system was 3.6 times that input to the model II system. Agricultural management emergy inputed to the model I system was less than that input to the model II system. The model I system had no emergy of fertilizers and pesticides devotion and more labour emergy to protect DDZ and save energy.

3.2. Production

The main crops grown in the model I system were lotus root, wild rice stem, cress, water chestnut, arrowhead, lettuce, water spinach. The output is mainly roots, stems and leaves (except water chestnut seed), and they can be harvested several times during a year. The main crop in the model II system is sesame, sweet potato, corn and rice, mainly for seed output (except sweet potato tubers), and these can be harvested once year. The products of model I system contain more vitamins and fibre and less starch and fat. The total energy yield transformed to ED is 3.99×10^{16} sej/year/ha (model I) and 4.00×10^{16} sej/year/ha (model II) (Fig. 5). In model I, the crops, such as water spinach (*Ipomoea aquatica*), lotus (*Nelumbo nucifera*[a]*)*, water chestnut (*Trapa bispinosa*), had a higher energy yield. In model II, the crops, such as rice (*Oryza sativa*[b]), sweet potato (*Ipomoea batatas*), had higher yield energy. The Chinese water chestnut (*Eleocharis dulcis*) in model I was similar to the sesame (*Sesamum indicum*) and maize (*Zea mays*) in the model II. All the crops in study, yield energy of rice (*Oryza sativa*[b]*) was* the hightest, was 2 or 3 times than sweet potato (*Ipomoea batatas*), water spinach (*Ipomoea aquatica*), water chestnut (*Trapa bispinosa*).

3.3. Emergy-based indices

The agriculture emergy yield ratio (AEYR) is a measure of the ability of a process to make local resources available by investing in outside resources: the higher the AEYR, the greater the contri-

Table 1
Category totals and indices calculated for the agriculture land systems under study.

Indices	Symbol & Formula	Description
Transformity	Tr	Unit emergy value. Generic expression of emergy investment per unit of product of reference flow (seJ g^{-1}; seJ J^{-1}, etc.). When the product is measured in energy units (J), it is more frequently termed transformity (seJ J^{-1}).
Renewable emergy	R	Renewable flows directly available to the system, such as solar radiation, wind and rain. Other renewable resources is recycle material, for example wood, bamboo, part of human labour.
Renewable emergy ratio	r%	The ratio of the renewable emergy invests divided by the total emergy driving the system.
Non-renewable emergy	N	Including local soil, labor, seeds, machinery, fertilizer, diesel fuel, pesticides, fertilizers, and other resources that are not replaced within an annual cycle. Non-renewable or slow-renewable emergy flows.
Investment material emergy	I	During crops growing, all the emergy flows imported from outside, purchased (fertilizer, diesel fuel, pesticides, fertilizers, seeds, instrument).
Management emergy	M	Indirect labor applies to reinforcement terraced farmland, plowing, weeding and harvesting, management of human contains application of fertilizers, pesticides, insecticides the investigated process.
Social emergy	S = I + M	Social emergy flows imported Investment material emergy and Management emergy.
Environment emergy	E	Nature emergy flows into agricultural system. Renewable natural resources may include solar radiation, wind, rain (chemical energy, geopotential energy). Non-renewable natural resources is mainly net topsoil loss.
Total input emergy	U = R + N; U = I + M + E	Total emergy flows needed to support a production system.
Agricultural yeilds emergy	AY	Agricultural yeilds is money received to the emergy embodied in the product exported to outside market.
Emergy density	ED	An indicator of the total emergy uses per unit area in a region or nation.
Agricultural emergy yeilds ratio	AEYR = AY/U	The ratio of the total emergy driving the system and the emergy purchased from outside. The index measures the emergy return on the emergy investment, i.e. the ability of a process to exploit local (renewable and non-renewable sources) by investing economic resources from outside.
Environmental loading ratio	ELR = N/R	Ratio of non-renewable (local and imported) emergy resources to the renewable emergyflows, indicating the load on the environment generated by human-dominated non-renewableflows.
Agricultural emergy sustainability index	AESI = AEYR/ELR	It is the composite ratio of the emergy yield ratio EYR to the environmental loading ratio ELR, indicating the process trade-off between the emergy advantage provided by the process and its environmental pressure.
The ratio Exergy/Emergy density	$R_{ex/em}$ = Ex/ED	The ratio Exergy/Emergy density can be regarded as the efficiency of an ecosystem, even though it is not dimensionless, as efficiency usually is, since it has the dimension of time. The higher its value, the higher the efficiency of the system in transforming the available direct and indirect solar energy into organization within the system.

Table 2
Emergy contributed by each flow in two systems.

Num.	Item	Unite	Raw data		Transformity (sej/unit)	Solar emergy (sej/yr)		Emergy density (sej/yr/ha)		Renewability factor
			Model I	Model II		Model I	Model II	Model I	Model II	
1	Sunlight	J/yr	5.15E + 13	1.09E + 14	1.00E + 00	5.15E + 13	1.09E + 14	2.60E + 13	2.86E + 13	1
2	Wind	J/yr	8.21E + 11	1.58E + 12	2.51E + 03	2.06E + 15	3.97E + 15	1.04E + 15	1.04E + 15	1
3	Rain, chemical energy	J/yr	5.11E + 11	1.03E + 12	3.12E + 04	1.59E + 16	3.28E + 16	8.04E + 15	8.58E + 15	1
4	Rain, geopotential energy	J/yr	1.56E + 11	3.01E + 11	4.66E + 04	7.28E + 15	1.40E + 16	3.67E + 15	3.67E + 15	1
5	River water	J/yr	1.37E + 11	1.40E + 10	8.13E + 04	1.12E + 16	1.14E + 15	5.63E + 15	9.04E + 14	1
6	Net topsoil loss	J/yr	4.64E + 08	8.94E + 08	1.24E + 05	5.75E + 13	1.11E + 14	2.90E + 13	2.90E + 13	0
7	Machine	J/yr	2.52E + 09	1.94E + 10	1.06E + 05	2.68E + 14	2.07E + 15	1.35E + 14	5.42E + 14	0
8	Fuel	J/yr	1.63E + 10	1.63E + 11	9.06E + 04	1.47E + 15	1.47E + 16	7.43E + 15	3.86E + 15	0
9	Seeds	J/yr	7.35E + 10	8.44E + 11	5.84E + 04	1.59E + 15	5.29E + 15	9.14E + 15	9.06E + 15	0.27
10	fertilizers	¥/m^2/yr	0.00E + 00	9.30E-01	2.42E + 11	0.00E + 00	2.25E + 11	0.00E + 00	5.88E + 10	0.05
11	pesticides	¥/m^2/yr	0.00E + 00	3.36E-01	2.42E + 11	0.00E + 00	8.12E + 10	0.00E + 00	2.13E + 10	0.05
12	reinforcement	¥/m^2/yr	6.75E-01	7.50E-02	2.42E + 11	1.63E + 11	1.81E + 10	8.22E + 10	4.74E + 09	0.05
13	plowing	¥/m^2/yr	2.03E + 00	9.00E-01	2.42E + 11	4.89E + 11	2.17E + 11	2.47E + 11	5.69E + 10	0.05
14	weeding	¥/m^2/yr	2.03E + 00	1.80E-01	2.42E + 11	4.89E + 11	4.35E + 10	2.47E + 11	1.14E + 10	0.05
15	harvesting	¥/m^2/yr	2.43E + 00	6.75E-01	2.42E + 11	5.86E + 11	1.63E + 11	2.96E + 11	4.27E + 10	0.05
16	Labor	J/yr	8.04E + 09	1.71E + 10	1.24E + 06	9.97E + 15	2.12E + 16	5.03E + 15	5.55E + 15	0.1

*sej/yr = sej/year; J/yr = J/year; $/yr = $/year.
Transformity for 1–5, 8 from Campbell et al. (2005); Transformity for 6,7 from Fu et al. (2011); Transformity for 9 from Lefroy and Rydberg (2003); Transformity for 10–15 calculated in this study from Jiang et al. (2009); Transformity for 16 from Vassallo et al. (2007).

bution to the economy and society around the system. The lowest possible AEYR is 1, indicating that a system is unable to exploit local resources and only transform resources from previous processes. In this study, the AEYR values of the two production models were 1.0 and 0.5, respectively (Fig. 6), showing that the process of model I was better able to exploit local resources and made a greater contribution to the development of the external environment than that of model II. The AEYR of the model I system is 1.0, which is similar to that of duck rearing (1.01), common mushroom cultivation (1.00) (Zhang et al., 2012), vegetables (1.05), rice-vegetables (1.07) (Lu et al., 2010). The model I system has better yield efficiency and is more competitive in the market.

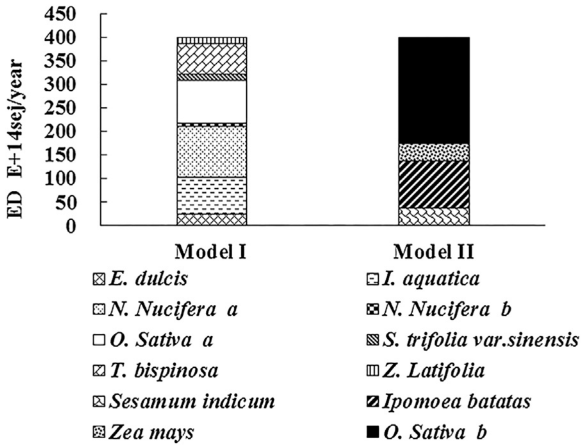

Fig. 5. The ED components of the crop production agriculture land systems.

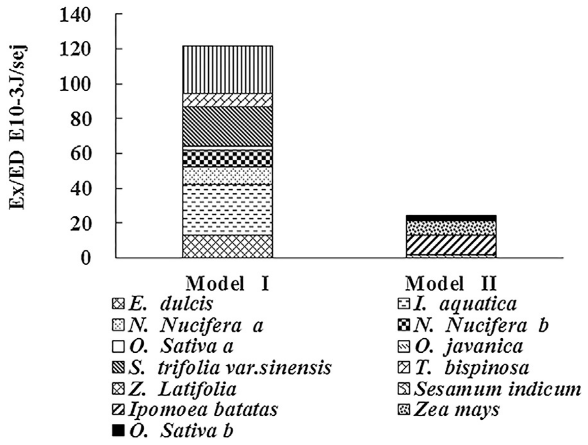

Fig. 7. The ratio of Exergy/Emergy density of the crop production agriculture land systems.

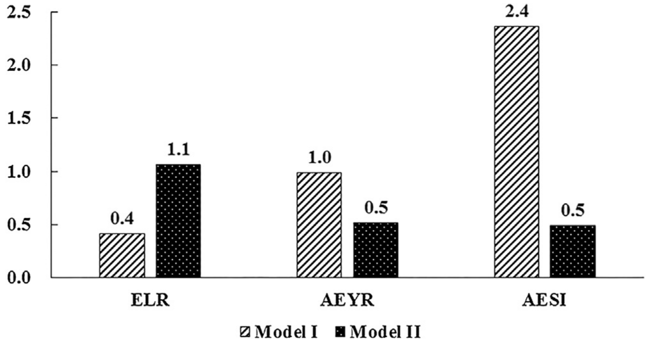

Fig. 6. Comparisons of emergy indices of different agricultural systems.

The environmental loading ratio (ELR) is an index of the pressure on the environment around the system. The concept of ELR is that once an environmental service is used by a process, it is not available for another process (Cavalett et al., 2006). Generally, ELRs of around two or less are indicative of relatively low environmental impacts (or of processes that can still use large areas of a local environment to 'dilute the impacts'); ELRs between 3 and 10 are indicative of moderate environmental impacts, while those above 10 indicate much larger environmental impacts due to large flows of concentrated nonrenewable emergy in a relatively small local environment (Brown and Ulgiati, 2004; Cavalett et al., 2006). The ELR obtained in this investigation of the model I production system and model II production system were 0.4 and 1.1, respectively. This suggests that the pressure placed by the model II production system on the environment is derived mostly from model II production system, which requires large amounts of nonrenewable emergy such as machinery, seeds, chemical fertilizer, pesticides and labour. The ELR of the model I system was 0.4, which is less than that of maize plantation (2.67), duck rearing (8.85), common mushroom cultivation (2.65), rice-vegetable system (1.38) and vegetables (5.50). However, the ELR value of the model I system in this case was similar to that of rice systems (0.62) in the Pearl River Delta.

The Agricultural emergy sustainability index (AESI) can be used to evaluate the sustainability of an agriculture system from an emergy viewpoint. A higher AESI indicates better sustainability of a system. Brown and Ulgiati (1997) demonstrated that systems had development vigor and potential when the AESI was between 1 and 10, whereas a value above 10 was indicative of an underdeveloped economic system due to insufficient local resources. The AESI of less than 1 meant that the system required a large energy input to be maintained. In this study, AESI values of the two model systems overall were 2.4 and 0.5, respectively (Fig. 6). This suggests that the model II production system has a low level of AESI under the current production mode. However, the value of the model I production system was 4 times greater than that of model II production system. In addition, the AESI of the model I system was higher than that reported for vegetables (0.19), and rice-vegetable (0.77) system, maize plantation (0.45), duck rearing (0.11), rice systems (1.83) and common mushroom cultivation (0.28) (Table 3).

3.4. Exergy to ED ratio

The ratio of Exergy to ED ($R_{ex/em}$) was the exergy yield of plants to the density associated with yields (ED = AY/Area) in our study, as the agriculture system in DDZ was highly artificial support systems and the yield of ED with different crops was the effective utilization emergy of agriculture system, which was different from forest system (Lu et al., 2011) and lagoon system (Bastianoni et al., 2006) with the emergy density related to total inputs (ED = U/Area). The $R_{ex/em}$ in two models of different agricultural system were 121.52×10^{-3} J/sej and 24.19×10^{-3} J/sej. The model I was more higher than model II. *I. aquatica* was the highest $R_{ex/em}$ (29.46×10^{-3} J/sej) in all crops, while *O. Sativa* was the lowest $R_{ex/em}$ (2.55×10^{-3} J/sej). *O. javanica* had not been harvested, so the $R_{ex/em}$ of amount was nothing (Fig. 7).

The two agricultural system were both artificial ecosystem. The main difference of both was that model I has been adopted ecological management mode (EMM) (Li et al., 2011). No fertilizers, herbicide and pesticides should be used, in order to reduce the nutrients be recruited from sedimentations during flooding and prevent chemical agents containing sulfur or copper from source. Bastianoni (1998) had indicated, when a microecosystem follows a process of selection and organization, researchers can use the ratio of exergy to emergy flow in order to assess the metabolic efficiency of an system in actual information and organization. The higher the ratio, the greater the efficiency of the ecosystem in transforming available inputs (as emergy) into structure and ecosystem organization (as exergy) (Bastianoni et al., 2006). The results obtained suggest a dependency on the 'age' of the system rather than on the difference between artificial and natural ecosystems. And close to the steady state (climax), the ratio of exergy to emergy flow tends to increase. This fact amplifies the role of the exergy to emergy ratio: when a system is relatively 'young', i.e. it is acquiring new inputs the ratio tends to be lower; on the other hand, when the system is developing on the available inputs the exergy to emergy ratio tends to rise as the system tends to the climax stage. So in this study, the model I agricultural system was a new method which

Table 3
Summary of emergy indices of other reported production systems.

Indices	Maize plantation	Duck rearing	Common mushroom cultivation	Rice	Vegetables	Rice & vegetables
EYR	1.20	1.01	1.00	1.15	1.05	1.07
ELR	2.67	8.85	2.65	0.62	5.50	1.38
ESI	0.45	0.11	0.38	1.83	0.19	0.77

Maize plantation, Duck rearing, Common mushroom cultivation (Zhang et al., 2012).
Rice, Vegetables, Rice & vegetables (Lu et al., 2010).

was quoted from classical agricultural system reflected ancestral farmers wisdom with ecological management mode (EMM), more older and more close to the steady state than model II which imprudent use of modern agricultural technology (fertilizers, herbicide and pesticides) could damage the environment, and could disturb the human–environment relationship.

4. Discussion

4.1. Renewable emergy input

All the emergy resources input, such as solar energy, rain, wind and river water in nature, are the absolute renewable inputs. During the input of social emergy resources, labour was the largest resource input in both of two model systems, as the renewable emergy ratio of labour was a forceful influence on each model system. The percentage of renewable and non-renewable emergy supporting labour in each of the systems (Ulgiati et al., 1994) was determined based on previous studies. In Sweden and Italy, two countries with living standards similar to the USA, 87% and 90%, respectively, of the emergy supporting labour was due to non-renewable sources (Panzieri et al., 2002; Rydberg and Jansén, 2002). Following the Swedish study, 87% of the emergy supporting labour was assumed to be non-renewable and 13% was assumed to be renewable for both systems in the United States. The non-renewable and renewable percentages of emergy supporting labour were 23% and 77%, respectively, for the indigenous system in calculated these percentages for agricultural households in Lacanja, Chiapas, Mexico. Guillen-Trujillo (1998) calculated these percentages for agricultural households in Frontera Corozal, Chiapas, which is located near. The emergy of crops could be reused partly, so the emergy resources input of crops had a renewable emergy ratio, such as mushroom strains, wheat straw, bean cake had renewable emergy ratios of approximately 27% (Zhang et al., 2012). Other materials, such as bamboo and timbers, could be used one more time, so renewable the emergy ratio was approximately 100% (Zhang et al., 2011). In this paper, other social emergy resources input had a renewable the emergy ratio, which we had assumed were labour (10%), crops (27%), purchase materials and payment to human labour (5%). Net topsoil loss, machines and fuel that could not be recycled had a renewable emergy ratio of zero. The renewable emergy input of each model system was shown in Table 2. The model I production system had more renewable emergy resources than the model II production system, but non-renewable emergy resources of both production systems were more than half the total emergy resources, which needs to be modified.

4.2. Economic analysis

The main crops grown in the model I system were lotus root, wild rice stem, stem, cress, water chestnut, arrowhead, lettuce and water spinach. The output is mainly roots, stems, and leaves (except water chestnut seed), etc., which can be harvested several times during a year. The main crop in the model II system is sesame, sweet potato, corn and rice, mainly for seed output (except sweet potato tubers), and these can be harvested once a year. The products of the model I system contain more vitamins and fibre and less starch and fat. In general, farmers living in the DDZ cannot be forbidden to cultivate this area. Their main purpose is to generate more income and improve their quality of life. The dike-pond system provides better income (80193.71 ¥/year) than conventional agriculture (64849.14 ¥/year) (Li et al., 2011), which could be increased by 23.66% approximately. Farmers have dwelled in DDZ of the TGR and have adopted conventional agriculture that uses fertilizer, herbicides and chemical pesticides to obtain less income and contaminate their surroundings, threatening their health. The dike-pond system is more appropriate to help them change this result.

4.3. The sustainable of agriculture model

After the industrial revolution, human society has been unprecedented in its destruction of the natural environment, and the consumption of non-renewable energy (original oil, coal and other fossil fuels) has increased sharply. According to the current global economic development rate, the majority of fossil fuel reserves have been used in less than 50 years, and most resources are almost exhausted. Currently, the human use of resources has assumed an unprecedented speed, soc-economic development cannot be sustained indefinitely, and the ecological environment is deteriorating, meaning that future generations will not have resources available. China is a large agricultural country, and the consumption of agricultural machinery and fuel is high. Today, agricultural production relies heavily on the consumption of non-renewable fossil fuels. In China between 1955 and 1992, there was a 100-fold increase in the use of fossil energy in agriculture for irrigation and for producing fertilizers and pesticides. Rationally optimizing the tillage method, appropriately decreasing the consumption of fuel, and progressively enhancing the effectiveness of agricultural machinery utilization, have had a positive effect on the sustainable development of economy, the environment and human society.

Fortunately, farmers have not ignored or abandoned the organic agricultural production systems that they have used traditionally. In China, many methods or models of organic agricultural production systems exist. Farmers have selected several crops and aquatic products to form different models, such as the “mulberry-fish pond”, “agriculture-dyke-fish pond”, “grass-dyke-fish pond”, “rice-duck-fish”, etc. The dike-pond project in the DDZ is similar to organic agricultural production systems but has some important differences. The organic rice-duck mutualism system indicates that the system had greater sustainability, lower environmental pressure, and higher resource-use efficiency (Xi and Qin, 2009). The dike-pond project in the DDZ has some emergy indices that are close to the organic rice-duck mutualism system (EYR = 1.82, ELR = 0.87 and ESI = 2.09). In the dike-ponds, many species of aquatic plants and animals can be planted and raised not only for direct economic reasons, but also for their functions in improving water quality and controlling soil erosion (Shen et al., 2010). Both emergy and energy evaluations between dike-pond projects and long-term rice production show that this as a similar production system for attaining sustainability. During the growing season for plants, a near-natural management mode was adopted.

No fertilizers are used, and the nutrients are recruited from sedimentation during flooding (Fang et al., 2006; Mitsch et al., 2008) as the fertilizers, pesticides and insecticides had not been widely used before. Plant diseases were prevented only through physical methods or microbes or products fermented by microbes, just like ducks have played a role in cleaning weeds and reducing insect pests in organic rice-duck mutualism systems. Which agriculture model was suitable in the DDZ of the Three Gorges Reservoir? As the abnormal undulation of water, long term submersion in the spring and autumn, flooding and drought in the summer, the agriculture model in the Pearl River Delta and Yangtze Delta were not the best and could not be operational in the DDZ, which has a different climate. The redesigned dike-pond agriculture model was better than conventional agriculture, could generate more income and improve farmer's quality of life and was better for the environment without chemical fertilizers and pesticides. It was more sustainable than conventional agriculture for society, economics, environment and ecology in the DDZ.

5. Conclusions

The target of this research was to use the emergy method to compare the resource use and environmental impact of dike-pond project farming systems as measures of their relative sustainability. This process was selected because it potentially provides a more comprehensive method of assessment than is possible when increasing renewable and non-renewable resource flows. The results provide as much insight into the assumptions inherent in this approach as they do into the farming systems under study.

The total emergy input to the model I system on the farm was 4.05×10^{16} sej/year, and the model II system on the farm 7.73×10^{16} sej/year. Based on this result, the total emergy input of the model I system was less than that of the model II system. The total yield energy transformed to ED is 3.99×10^{16} sej/year/ha (model I) and 4.00×10^{16} sej/year/ha (model II). In model I, the crops, such as water spinach (*Ipomoea aquatica*), lotus (*Nelumbo nucifera*[a]*)*, water chestnut (*Trapa bispinosa*), had a higher energy yield. In model II, the crops, such as rice (*Oryza sativa*[b]), sweet potato (*Ipomoea batatas*), had higher yield energy. The $R_{ex/em}$ in the two models of different agricultural system were 121.52×10^{-3} J/sej and 24.19×10^{-3} J/sej. The dike-pond agriculture model redesigned was better than conventional agriculture, could generate more income and improve the quality of life for the farmer and was more ecological without chemical fertilizers and pesticides. In this study, the AESI values of the two model systems overall were 2.4 (model I) and 0.5 (model II), respectively. This suggests that the model II production system has a low level of AESI under the current production mode. The environment of the reservoir had a further impact that led to a small change in a short period of aquatic crops. The yield was not volatile. It would not cause crops to be destroyed and the adaptability and sustainability would not wildly change.

The dike-pond project in the DDZ is similar to the organic rice-duck mutualism system and the results indicate that the system had greater sustainability, lower environmental pressure, and higher resource-use efficiency than conventional agriculture. No fertilizers should be used because the nutrients are recruited from sedimentation during flooding to the dike-pond project and no chemicals should be used because the fertilizers, pesticides and insecticides had not been widely used before. Compare to the traditional rice-fish co-culture system, the dike-pond project reduces costs for farmers because pesticide and fertilizer use is lower while yields remain similar to those obtained in a rice monoculture. This method was more sustainable than conventional agriculture for society, the economy, the environment and ecology in the DDZ.

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